

Some Geotechnical Properties of Plastic Soil Enhanced with Cement Dust

Abeer F. Hussein *
Institute of Technology-Baghdad,
Middle Technical University,
Baghdad, Iraq
abeerfhussein@gmail.com

Ahmed S. Ali
.Assist. Prof
College of Engineering, Al-Nahrain
University Baghdad-Iraq
ahmed_sltn2007@yahoo.com

Abbas J. Al-Taie
.Assist. Prof
College of Engineering, Al-Nahrain
University Baghdad-Iraq
abbasjaltaie@yahoo.com

ABSTRACT

Plastic soil exhibits unfavorited geotechnical properties (when saturation), which causes negative defects to engineering structures. Different attempts (included various materials) were conducted to proffer solutions to such defects by experimenting in practical ways. On one hand, these attempts aimed to improve the engineering characteristics of plastic soil, and on the other hand, to use problematic waste materials as a stabilizer, like cement kiln dust, and to reduce environmental hazards. This paper explored the shrinkage, plasticity, and strength behavior of plastic soil enhanced with cement dust. The cement dust contents were 0%, 5%, 10%, 15% and 20% by dry weight of soil. An experimental series of shrinkage and plasticity tests and unconfined compression tests were carried out to explore the effects of cement dust on the quantitative amount of shrinkage, plasticity characteristics, and shear strength experienced by plastic soil. The effects of curing on soil strength were also investigated. The finding of this paper showed that the critical behavior and plasticity of plastic soil could be reduced by mixing the soil with 15% or 20% of cement dust. The undrained shear strength, c_u , of plastic soil-cement dust mixtures increased with the increasing dust content up to 20%. In fact, this strength was affected by the curing period. The best enhancement was attained when the content of cement dust was 20%, and the undrained shear strength was increased more than three times at this content.

Keywords: Plastic soil, cement dust, undrained strength, curing shrinkage, plasticity, stabilization.

بعض الخصائص الجيوتكنيكية للتربة البلاستيكية المحسنة بغبار السمنت

عباس جواد الطائي
استاذ مساعد
كلية الهندسة، جامعة النهرين

احمد سلطان علي
استاذ مساعد
كلية الهندسة، جامعة النهرين

عبير فواد حسين*
ماجستير
المعهد التقني-بغداد، الكلية التقنية الوسطى

الخلاصة

تظهر التربة البلاستيكية خصائص جيوتكنيكية غير مرغوب بها عند التشبع والتي تتسبب بتأثيرات سلبية للهياكل الهندسية. بذلت محاولات عديدة من قبل الباحثين لإيجاد حل لهذه العيوب من خلال استخدام الطرق التجريبية المختبرية. تضمنت هذه المحاولات

*Corresponding author

Peer review under the responsibility of University of Baghdad.

<https://doi.org/10.31026/j.eng.2021.10.02>

2520-3339 © 2019 University of Baghdad. Production and hosting by Journal of Engineering.

This is an open access article under the CC BY4 license <http://creativecommons.org/licenses/by/4.0/>.

Article received: 17/8/2019

Article accepted: 3/11/2019

Article published: 1/10/2021



مواد مختلفة يمكن أن تحسن الخصائص الهندسة للتربة وتستخدم المواد والمخلفات ذات المشاكل (مثل مادة غبار السمنت) لتقليل من المخاطر البيئية لها. بحثت هذه الورقة في سلوك وخصائص الانكماش واللدونة ومقاومة القص الطين البلاستيكي المحسن بمادة غبار السمنت. كانت محتويات غبار السمنت هي 5% و 10% و 15% و 20% من الوزن الجاف للتربة. تم إجراء سلسلة من فحوصات الانكماش الخطي واللدونة واختبارات النضج غير المحصور لدراسة تأثير غبار السمنت على التربة البلاستيكية المحسنة. تمت دراسة تأثير الانضاج على مقاومة قص للتربة في هذا البحث. وجد أن السلوك الحرج واللدونة للتربة يمكن تقليله بخلطها مع 15% أو 20% من غبار السمنت. تزداد مقاومة القص الغير الميزولة للتربة الممزوجة بغبار السمنت بزيادة نسبة غبار السمنت المستخدم بنسبة تصل إلى 20%. هذه القيم تأثرت بفترة الانضاج. تم تحقيق أفضل تثبيت عندما استخدم المحتوى الأمثل من غبار السمنت، 20%. أخيرًا، وجد ان انضاج التربة المحسنة بغبار السمنت لمدة سبعة أيام حسن مقاومة القص بأكثر من 100%

الكلمات الرئيسية: الطين البلاستيكي، غبار السمنت، مقاومة القص الغير ميزولة، الانضاج، الانكماش الخطي، حدود القوام.

1. INTRODUCTION

Plastic soils are expansive in nature and have sensitive geotechnical properties upon wetting/drying at which, their behavior changed drastically. Such soils would increase in volume when saturated, and therefore, would lose their strength, and the shrinkage happens when the soils get dry. The loss of strength and volume reduction of this soil can cause negative impact and damage on civil engineering constructions (roads, buildings, pipelines, etc.) which, in some cases, is even more than the damages of hurricanes, floods, earthquakes, and tornadoes. Improving the geotechnical properties of these types of soils can help to control the imposed damages to the structures (Jones and Jefferson, 2012); (Al-Busoda and Abbase, 2015a); (Khademi and Budiman, 2016) and (Al-Baidhani and Al-Taie, 2020).

Different researches studied the possibility of enhancing these soils by mechanical methods (e.g., soil compaction) (Al-Taie and Al-Shakarchi, 2016), or by adding materials such as lime, cement, and adding river mixture soil (Abdullah and Alsharqi, 2011); (Hamad, 2014); (Mishra and Mishra, 2015); (Al-Busoda and Abbase, 2015b); (Ahmed and Hamza, 2015), or mixing with chemical additives (Ismail, 2013); (Keanawi and Kamel, 2013). In the last years, nontraditional materials, like solid wastes, were also used. These materials included fly ash, quarry waste, silica fume, cement kiln dust, tire rubber, rice husk, etc., (Pandian, 2004); (Peethamparan and Olek, 2008); (Ahmed and Adkel, 2017); (Wu, et al., 2019); (Dutta, et al., 2019); (Mujtaba, et al., 2019). However, some of these materials cause negative effects on the nature (Yuna, et al., 2019). In recent times, efforts have been made to use dust materials from cement factories as a stabilizer agent for engineering soils (Bhatti, et al., 1996); (Miller and Azad, 2000); (Taha, et al., 2001); (Shabel, 2006); (Abdullah, 2009); (Albusoda and Salem, 2012); (Okafor and Egbe, 2013); (Jwaida, et al., 2017); (Rimal, et al., 2019). These materials chemically reacted (in the presence of water) with soils and produced physicochemical reactions in the soil matrix (Ikeagwuani and Nwonu, 2019). Unfortunately, the results of these studies are sporadic regarding the applicability of cement dust material in geotechnical engineering.

For example, (Taha, et al., 2001) and (Jwaida, et al., 2017) found that using cement dust as a soil stabilizer increased the liquid and plastic limits of soil; while (Jala and Sharma, 2019) recorded a decrease in soil liquid limit with increasing cement dust up to 10% then this limit goes to decrease with further increase in dust material, also these authors found that the plastic limit was not effected with the addition of cement dust., In contrast, (Ismail, 2013) stated that the addition of cement dust reduced the values of Atterberg limits (liquid limit, plastic limit, and plasticity index). On the other hand, the compaction characteristics of soils exhibited a varied response to cement dust addition. Some researchers showed that the optimum water content significantly increased with increasing cement dust, other studies showed a slight increase in water content, while the values



of optimum moisture content (OMC) and maximum dry density (MDD) showed a slight decrease in some cases, (Taha, et al., 2001); (Rahman, et al., 2011); (Al-Homidy, et al., 2017).

This study reported laboratory testing results to investigate the influence of mixing cement dust with plastic soil. The undrained shear strength, plasticity, and shrinkage properties were explored experimentally. The effect of different curing periods on the undrained shear strength was also, included in this paper.

2. MATERIALS USED

The plastic soil used in this paper was obtained from the middle of Iraq. The soil has a liquid limit and plasticity index of 59 and 27, respectively, **ASTM D 4318**. It has high liquid limit and plasticity index values, and in accordance with **ASTM D 2487**, the soil can be classified as MH. The specific gravity of the soil is 2.65, **ASTM D854**. According to the standard compaction test, **ASTM D698**, the soil has a maximum dry unit density of 1.52 t/m^3 , and optimum moisture content is 22%. The second material used in this study as a stabilizer is cement dust. Cement dust is the waste obtained from a local cement factory; it is a byproduct of waste material (free available). It is non-plastic material with a specific gravity of 2.90, **ASTM D854**.

3. SAMPLES PREPARATION AND METHODOLOGY

Mixtures of plastic soil and cement dust have been prepared. The standard compaction test of plastic soil was carried out in order to obtain the optimum water content and maximum dry density. The contents of cement dust were 5%, 10%, 15%, and 20%. During all the tests, the plastic soil and cement dust were dry mixed, the prespecified required water was added to the dry mixtures, and the produced wet mixture was well mixed to produce homogenous soil-cement dust mixtures. These mixtures were compacted according to **ASTM D854**. Atterberg limits were determined for soil-cement dust mixtures as per **ASTM D4318**. The linear shrinkage of the soil-cement dust mixtures was determined as per **BS 1377**. The remolded samples were prepared at high moisture content, placed in a metal mold, and then placed in an oven to dry at $105 \text{ }^\circ\text{C}$ to $110 \text{ }^\circ\text{C}$. After 24 hours, the length of the soil bar was measured carefully. For the unconfined compression test (UCT), samples of soil-cement dust mixtures were compacted to optimum water content and the maximum dry density. For each soil-cement dust mixture, three samples were prepared. The first sample was tested directly after preparation, while the rest were cured for (3 and 7) days before testing. **Fig. 1** shows the cured samples, test set up and tested samples. Undrained shear strength of the natural soil and soil-cement dust mixtures were determined from the unconfined compression test. A series of unconfined test was carried out according to **ASTM D2166**.



During curing

Samples testing

Failure of samples

Figure 1. Samples of unconfined compression test.

4. RESULTS AND DISCUSSION

Plastic soil is sensitive to wetting and drying cycles. Linear shrinkage can be used to calculate the quantitative amount of shrinkage experienced by cohesive soil, BS 1377. This factor is suitable to converse condition of expansion due to wetting. In this study, the linear shrinkage was measured for soil before and after mixing with cement dust. The final drying stages of the shrinkage test for soil-cement mixtures are shown in **Fig. 2**. The final values of linear shrinkage were calculated from the test results and presented in **Fig. 2**. As shown, the soil sample with 0% cement dust revealed high shrinkage; the shrinkage behavior for such soil may be critical (**Altmeyer, 1956**). It is expected that this soil's expansive behavior is critical (high expansive behavior), Holtz et al., 2011. As an attempt to decrease the negative effect of this behavior, plastic soil was mixed with 5%, 10%, 15%, and 20% of cement dust and shrinkage have been measured, **Fig. 2**. As can be seen in **Fig. 2**, the mixing of 5% of cement dust has a negative effect on the value of linear shrinkage where the linear shrinkage value was increased at this content. With further increases in dust content (above 5%), the plastic soil's linear shrinkage was decreased. The total reduction percent in linear shrinkage was 55% at cement dust content 20%. These positive results indicate that the critical behavior of plastic soil (high shrink/swell) can be mitigated by mixing the soil with 20% of cement dust.

In this study, the sporadic researches regarding the effect of cement dust on soil plasticity had been investigated. A series of Atterberg limits tests were carried in accordance with ASTM standards. As in the shrinkage test, plastic soil was mixed with 5%, 10%, 15%, and 20% cement dust then Atterberg limits were determined. **Fig. 3** shows the tests result. It is clear that the results of the liquid limit are compatible with linear shrinkage, where the mixing of 5% of cement dust led to an increased liquid limit value. For mixtures with cement dust greater than 5%, the general behavior of the plastic soil coincides with that presented by (**Jala and Sharma, 2019**). The addition of 10%, 15%, and 20% of cement dust reduced the liquid limit of plastic soil. In general, cement dust caused an increase in plastic limit and a decrease in soil plasticity. Also, there is very slight or no change in plastic limit values that can be noticed for dust content greater than or equal to 10%. The general conclusion is liquid limit and plasticity index go to decrease when plastic soil is mixed with 10% or more cement dust. In contrast, the plastic limit goes to increase with increasing dust content up to 10%, above this content, the plastic limit, almost was not affected.

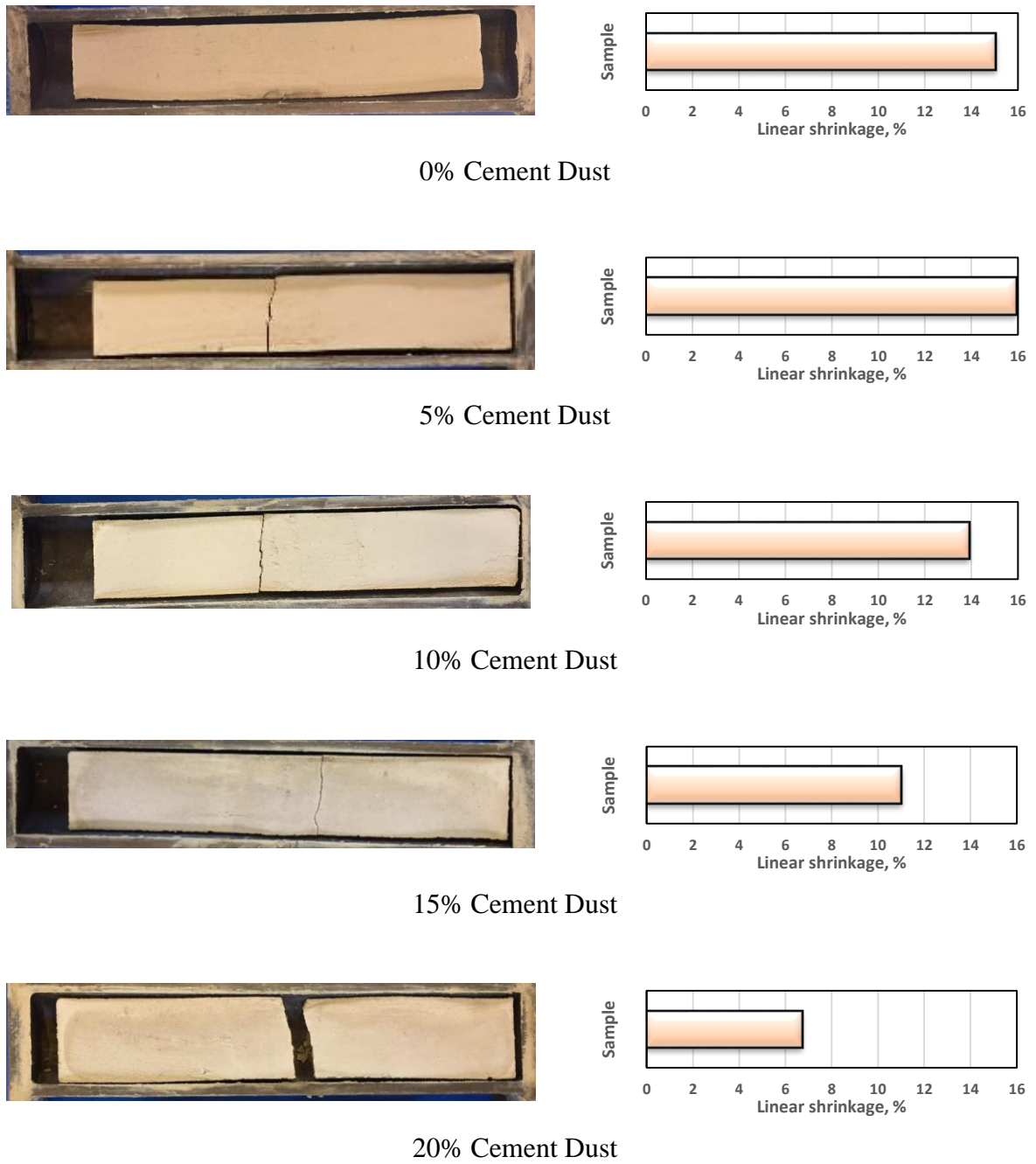


Figure 2. Final Stage Samples and Measured values from linear shrinkage for soil-Cement dust mixtures.

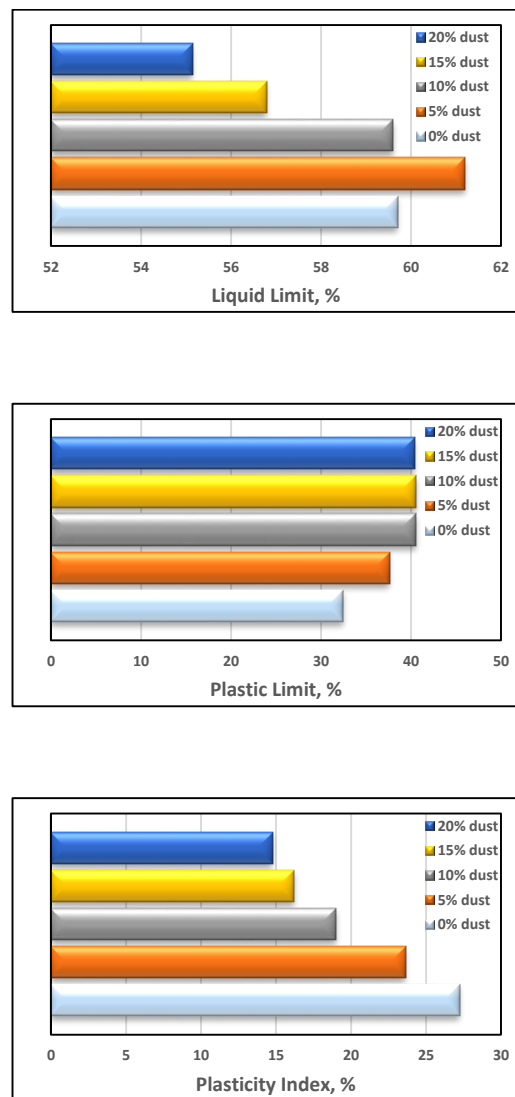


Figure 3. Effect of cement dust on Atterberg Limits values.

The optimum cement dust content required to improve the shear strength of plastic soil has been studied in this paper. The soil was mixed with different contents of cement dust, and samples were prepared at optimum water content and maximum dry density. Then a series of unconfined tests were carried out according to **ASTM D 2166**. The cement dust content varied from 5% to 20%, with an increase of 5%. Three groups of samples were tested. In the first group, the samples were tested directly after preparation to obtain the undrained shear strength of soil-cement dust mixtures, **Fig.4**, while the samples in the second and third groups were cured for a while of time before testing. It is obvious that samples that tested directly with 15% of cement dust possess a maximum undrained shear strength, c_u . Also, one can be seen that the c_u values for soil with 10% and 20% of cement dust are very closed to c_u value of natural soil. Accordingly, the mentioned dosage (i.e., 15%) was chosen as optimum dust content to improve the undrained shear strength of compacted plastic soil. On the other hand, the addition of 5% of cement dust has a negative effect on the shear



strength of plastic soil. This negative effect is compatible with that in liquid limit and shrinkage tests.

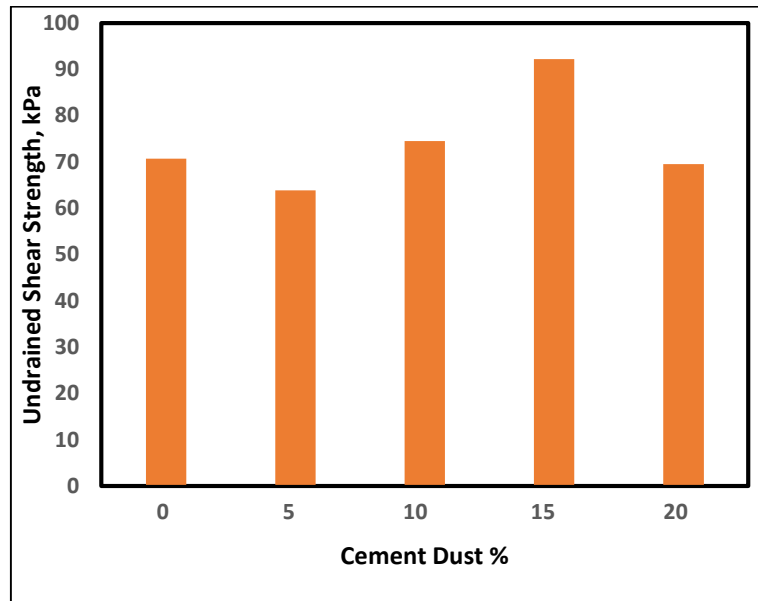


Figure 4. Undrained shear strength of soil-cement dust mixtures (without curing).

Fig. 5 shows that the c_u values of treated plastic clay are highly affected by the curing period. In general, an increase in c_u values can be observed for different cement dust contents. The curing caused an improvement in c_u values for different degrees. The soil samples stabilized with 15% and 20% of cement dust are seen highly affected by the curing period. **Table 1** presents the improvement ratio (the difference between c_u of soil without cement dust and c_u of clay with different cement dust contents) cement dust divided by c_u of soil without cement dust), with curing time (3 and 7) days. For each dust content, the improvement ratio is proportioned to curing period, best improvement ratio was recorded for dust content of 20%, while the least improvement ratio was recorded for soil samples with 5% cement dust. The 3- and 7-days improvement ratio's exceeded 100% for soil with more than 10% dust, furthermore, the undrained shear strength was increased more than three times when plastic soil that mixed with 20% cement dust was cured for seven days. Accordingly, the mentioned curing period can be adopted as optimum curing period with optimum dust content (20%) to improve the undrained shear strength of compacted plastic soil.

Table 1. Improvement ratio with curing time.

Curing Period, days	Cement Dust %			
	5	10	15	20
0	-3.4	12.7	39.5	5.2
3	47.2	138.2	263.2	216.8
7	89.1	245.0	255.5	384.2

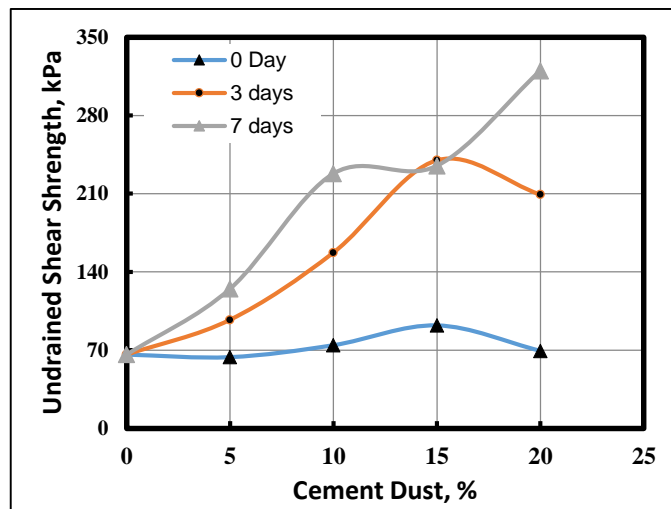


Figure 5. Undrained shear strength of soil-cement dust mixtures.

The stress and strain behavior of soil-cement dust mixtures have been studied. Figs. 6 to 8 present stress-strain relationships (from unconfined test results) for soil mixed with different contents of cement dust and cured for different periods. It can be noted that the relationship for the soil without dust is of ductile behavior. In comparison, the pattern of stress and strain relationships for soil-cement dust mixtures are of brittle nature. This behavior is more pronounced in Figs. 7 and 8, as the curing period increased, higher strength was recorded with less axial strain. With a 7 days period, mixtures of soil with 15% and 20% cement dust showed the same brittle pattern with higher strength and less strain. Fig. 9 shows the variation of strain failure with dust contents for different curing periods. A particular effect of 3days curing on the failure strain can be noted for dust content below 15%; the curing reduces the failure strain of the mixtures. For all periods of curing, similar failure strains are noted at a dust content of 15%.

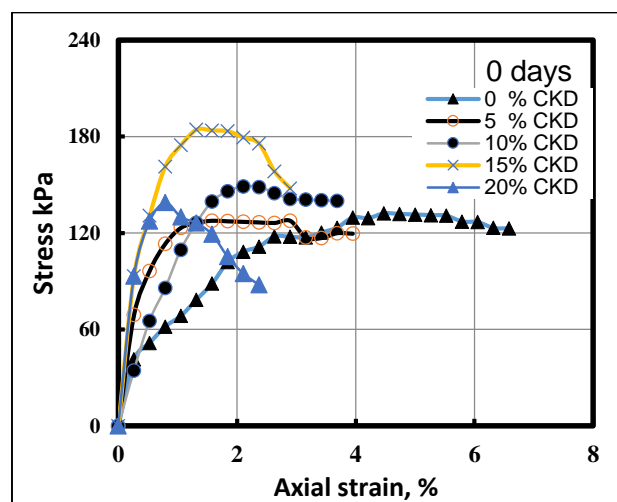


Figure 6. Stress-strain relationships for soil-cement dust mixtures without curing.

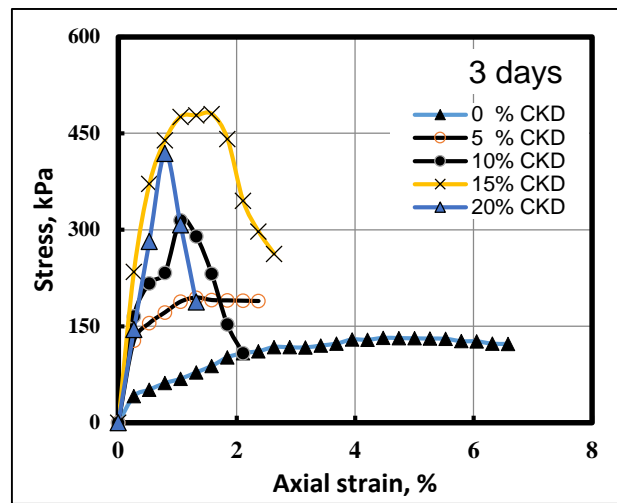


Figure 7. Stress-strain relationships for soil-cement dust mixtures cured for 3 days.

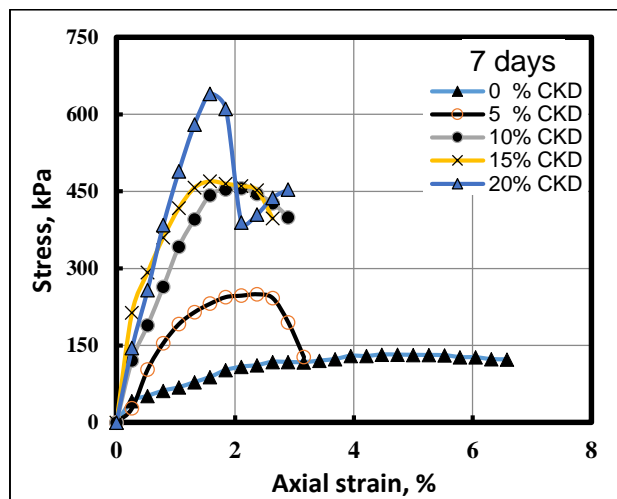


Figure 8. Stress-strain relationships for soil-cement dust mixtures cured for 7 days.

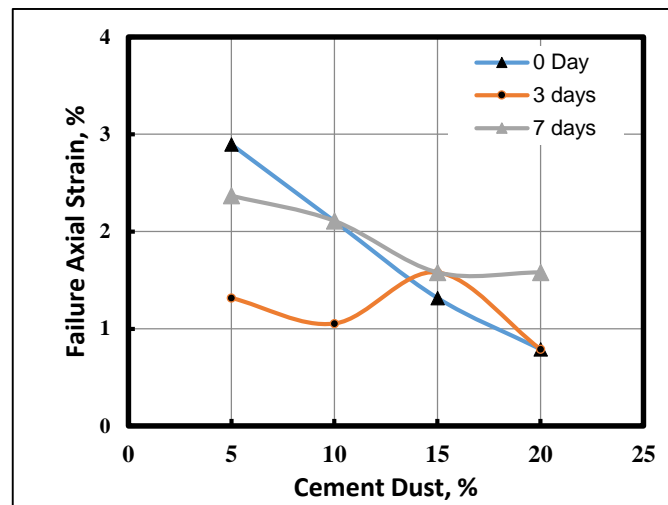


Figure 9. Variation of strain failure with dust contents for different curing periods.

5. CONCLUSIONS

This study presents the results of experimental testing carried out to investigate the effects of cement dust on shrinkage, plasticity, and strength properties and behavior of plastic soil. The results show that the shrinkage of the plastic soil decreases with increasing the dust content. The critical behavior of plastic soil (high shrink/swell) can be mitigated by mixing with 15% or 20% of cement dust. Regarding soil plasticity, the liquid limit and plasticity index go to decrease when plastic soil is mixed with 10% or more cement dust; in contrast, the plastic limit goes to increase with increasing dust content up to 10%, above this content, the plastic limit, almost are not affected. The undrained shear strength, c_u , of plastic soil mixed with 10% or 20% cement dust are very closed to c_u of natural soil. The dosage of 15% of cement dust can be chosen as an optimum dust content to improve the undrained shear strength of compacted plastic soil. The undrained shear strength increases more than three times when plastic soil is mixed with 20% cement dust and curried for seven days. The pattern of stress and strain relationships for soil-cement dust mixtures are of brittle nature, while it is of ductile behavior for natural soil. As the period of curing increases, higher strength is recorded with less axial strain. The period of curing plays a major role in the stabilization of soil with cement dust. Thus further study for 28 days curing is recommended. Finally, it found that adding 5% of cement dust has a negative effect on the shrinkage factor, liquid limit, and shear strength of plastic soil.

REFERENCES

- Abdullah, G.M.S., 2009. *Stabilization of eastern Saudi soils using heavy fuel oil fly ash and cement kiln dust*. MS Thesis. Dhahran, Saudi Arabia.
- Abdullah, W.S., and Alsharqi, A.S., 2011. Rehabilitation of medium expansive soil using cement treatment. *Jordan Journal of Civil Engineering*, 159.2985, pp., 1-14.



- Ahmed, M., and Hamza, N., 2015. Effect of Metakaolin on the geotechnical properties of Expansive Soil. *Journal of Engineering*, 21(12), pp., 29-45. <http://joe.uobaghdad.edu.iq/index.php/main/article/view/288>.
- Ahmed, M., and Adkel, A., 2017. Stabilization of clay soil using tyre ash. *Journal of Engineering*, 23(6), pp., 34-51. <http://joe.uobaghdad.edu.iq/index.php/main/article/view/31>.
- Al-Baidhani, A., Al-Taie, A. J., 2020. Shrinkage And Strength Behavior Of Highly Plastic Clay Improved By Brick Dust. *Journal of Engineering*, 26(5), pp., 95-105. DOI: 10.31026/j.eng.2020.05.07
- Al-Busoda, B.S., and Abbase, H.O., 2015a. Measurements of suction and water content during saturation of compacted expansive soil. *Diyala Journal of Engineering Sciences*, pp., 100-109.
- Al-Busoda, B.S., and Abbase, H.O., 2015b. Mitigation of Expansive Soil Problems by Using Helical Piles with Additives. *Journal of Geotechnical Engineering*, 3(2), pp., 30-40.
- Albusoda, B. S, and Salem, L. K., 2012. Stabilization of Dune Sand by Using Cement Kiln Dust (CKD). *Journal of Earth Sciences and Geotechnical Engineering*, 2(1), pp., 131-143.
- Al-Homidy, A.A., Dahim, M.H., and Abd El Aal, A.K., 2017. Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust. *J. Rock Mech. Geotech. Eng.*, 9 (4), pp.,749–760. <https://doi.org/10.1016/j.jrmge.2016.11.012>.
- Al-Taie, A. J., and Al-Shakarchi, Y., 2016. *Dune Soils of Mesopotamian Plain as Geotechnical Construction Material*. LAP LAMBERT Academic Publishing.
- Altmeyer, W.T., 1956. Discussion following paper by Holtz and Gibbs. *Transactions of the American Society of Civil Engineers*, 2(1), pp., 666–669.
- ASTM D2166, 2017. *Standard Practice for Unconfined Compressive Strength of Cohesive Soil*, Book of Standards Volume: 04.08.
- ASTM D2487, 2017. *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, Book of Standards Volume: 04.08.
- ASTM D4318, 2017. *Standard Practice for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, Book of Standards Volume: 04.08.



- ASTM D854, 2017. *Standard Practice for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft³ (600 kN-m/m³))*. Book of Standards Volume: 04.08.
- ASTM D854, 2017. *Standard Practice for Specific Gravity of Soil Solids by Water Pycnometer*, Book of Standards Volume: 04.08.
- Bhattu, J.I., Bhattacharja, S., and Todres, H.A., 1996. Use of Cement Kiln Dust in Stabilizing Clay Soils. *Portland Cement Association*, PCA Serial No. 2035, Skokie, Illinois, USA, pp., 28.
- BS 1377:1990 -*Methods of test for soils for civil engineering purposes*.
- Dutta, R. K., Khatri, V.N., Thakur, V., and Das, P. P., 2019. Effect of alccofine addition on the index and engineering properties of bentonite. *Journal of Geotechnical Engineering*, 6(1), pp., 9–17.
- Hamad, A.A., 2014. Expansive soil stabilization by adding river mixture soil. A study submitted to the Kurdistan Engineers Union, Iraq.
- Holtz, R. D., Kovacs, W. D. and Sheahan, T. C., 2011. *An Introduction to Geotechnical Engineering*, 2nd edition, Pearson.
- Ikeagwuani C.C, and ,Nwonu D. C., 2019. Emerging trends in expansive soil stabilisation: A review. *J Rock Mech Geotech Eng.*, 11(2), pp., 423-440. <https://doi.org/10.1016/j.jrmge.2018.08.013>.
- Ismaiel, A.H., 2013. Cement kiln dust chemical stabilization of expansive soil exposed at El-Kawther Quarter, Sohag Region, Egypt. *International Journal of Geosciences.*, pp., 1416-1424.
- Jala S.K., and Sharma P., 2019. Effect of Cement Kiln Dust and RBI Grade 81 on Engineering Properties of Plastic Clay. In: Agnihotri A., Reddy K., Bansal A. (eds) *Recycled Waste Materials. Lecture Notes in Civil Engineering*, vol 32. Springer, Singapore.
- Jones, L. D., and Jefferson I., 2012. *Expansive Soils*. ICE Publishing, 413-441.
- Jwaida, Z., Dulaimi, A., Jafer, H.M., Atherton, W., and Al-Kafaji, R., 2017. Soft Subgrade Stabilisation Using Cement Kiln Dust and Ground Granulated Blast Slag . *The 3rd BUiD Doctoral Research Conference 2017*, British University, Dubai.



- Keanawi, M. A., and Kamel, A.O., 2013. Durability of expansive soil treated by chemical additives. *International Journal of Engineering and Innovative Technolog*, 3(1), pp., 315-319.
- Khademi, F, and Budiman, J., 2016. Expansive soil: causes and treatments. *J-manager's Journal on Civil Engineering*, 6(3), pp., 1-13.
- Miller, G.A., and Azad, S., 2000. Influence of soil type on stabilization with cement kiln dust. *Construction and Building Materials*, 14(2), pp.,89-97. [https://doi.org/10.1016/S0950-0618\(00\)00007-6](https://doi.org/10.1016/S0950-0618(00)00007-6)
- Mishra, B., and Mishra, R. S., 2015. Improvement in characteristics of expansive soil by using quarry waste and its comparison with other materials like cement and lime being used for soil improvement. *International Journal of Innovative Research in Science, Engineering and Technology*, 4(8), pp., 7416-7431.
- Mujtaba, H., Aziz, A., Farooq, K., Sivakugan, N., and Das, B., 2019. Improvement in engineering properties of expansive soils using ground granulated blast furnace slag. *Journal of the Geological Society of India*, 92(3), pp., 357–36.
- Okafora, F.O., Egbab, E.A. (2013) Potentials Of Cement Kiln Dust In Sub-Grade Improvement. *Nigerian Journal of Technology (NIJOTECH)*, 32(1): 109–116.
- Pandian, N. S., 2004. Fly ash characterization with reference to geotechnical applications. *Journal of the Indian Institute of Science*. 84(6) .
- Peethamparan, S., and Olek, J., 2008. Study of the effectiveness of cement kiln dusts in stabilizing Na-montmorillonite clay. *Journal of Materials in Civil Engineering, ASCE.*, 20(2), pp., 137-146.
- Rahman, M. K., Rehman, S., and Al-Amoudi, O.S.B., 2011. Literature review on cement kiln dust and waste stabilization and experimental investigation. *International Journal of Research and Reviews in Applied Sciences*, 7(1), pp., 77-87.
- Rimal, S., Poudel, R.K., and Gautam, D., 2019. Experimental study on properties of natural soils treated with cement kiln dust. *Case Studies in Construction Materials*, 10, e00223. <https://doi.org/10.1016/j.cscm.2019.e00223>
- Shabel I. M., 2006. *Stabilization of Jazan sabkha soil using cement and cement kiln dust*. MS Thesis. Riyadh, Saudi Arabia: Department of Civil Engineering, King Saud University (in Arabic).



- Taha, R., Al-Rawas, A., Al-Harthy, A., and Al-Siyabi, H., 2001. Use of cement by-pass dust in soil stabilization. *Engineering Journal of the University of Qatar*, 14, pp., 61-76.
- Wu, J., Liu, Q., Deng, y., Xinbao Yu, X., Fen,g Q., and Yan, C., 2019. Expansive soil modified by waste steel slag and its application in subbase layer of highways. *Soils and Foundations*. <https://doi.org/10.1016/j.sandf.2019.03.009>.
- Yuna, K., Ruttera, A., Zeebab, B.A., 2019. Composting of halophyte *Phragmites Australis* following phytoaccumulation of chloride from a cement kiln dust (CKD)-contaminated landfill. *Waste Management*, 87, pp., 119-124. <https://doi.org/10.1016/j.wasman.2019.01.030>Get rights and content

NOMENCLATURE

cu = undrained shear strength, kPa.

UCT = unconfined compression test.